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PREDICTION OF PROPELLANT AND EXPLOSIVE COOK-OFF FOR THE 30-MM HEI-T AND RAUFOSS MPLD-T ROUNDS CHAMBERED IN A HOT MK44 BARREL (ADVANCED AMPHIBIOUS ASSAULT VEHICLE – AAAV)

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An analytical thermal study was conducted of the 30-mm MK44 barrel and two high-explosive rounds to determine the relationship between the number of rounds fired and the time to initiate propellant and explosive cook-off in a misfired round that remains in the barrel. The barrel temperature distribution during firing was calculated using the FDHEAT finite difference heat-transfer program, with film coefficients and gas temperatures being supplied by the XNOVAKTC interior ballistics program. Heat transfer between the barrel, projectile, and the environment during a simulated misfire event was modeled using the ABAQUS finite element program with the initial barrel temperature distribution, associated with a particular number of rounds fired, being supplied by FDHEAT. Propellant cook-off calculations were made by assuming that cook-off would occur when the transient temperature profile at the inside of the case, in the shoulder region, exceeded an experimentally based cook-off curve developed for M2 double-base propellant. Explosive cook-off calculations were made by assuming that cook-off would occur when any small volume of explosive material in the finite element model experienced thermal runaway. In order to be able to simulate the initiation of explosive cook-off in the finite element model, it was necessary to include an Arrhenius-type heat generation equation as part of the explosive's material definition. Two rounds were considered in the study, the High Explosive Incendiary with Tracer (HEI-T) and the Raufoss Multi-Purpose, Low Drag with Tracer (MPLD-T), each containing PBXN-5 explosive. The Raufoss round also contained the Comp-A4 explosive that was also considered an explosive cook-off candidate. Predicted barrel and projectile temperature profiles showed good agreement with barrel and instrumented round thermocouple test data generated during a 20,000 round wear and performance test conducted by Boeing Ordnance from 1 November 1999 to 15 December 1999 in Mesa, Arizona. Analysis results showed a conservative prediction of propellant cook-off times when compared with experimental cook-off times generated using live rounds loaded into pre-fired (hot) barrels during the Boeing test. One important result of the cook-off study showed that, for a barrel and round at an initial temperature of 70°F (21.1°C), cook-off of either the propellant or the explosive was not predicted to occur before 160 rounds had been fired, using either a 524-round magazine fire-out (combat tactical schedule) or a 524-round magazine fire-out (continuous burst at 200 rounds/minute).

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INTRODUCTION

The 30-mm MK44 cannon is currently under development for use on the Navy/Marine Corps Advanced Amphibious Assault Vehicle (AAAV). In order for manned firing of the gun to be permitted, it must be demonstrated that the gun can be operated in a safe manner under anticipated firing conditions. In practice, the soldier operating this weapon will need to rely on safety procedures that describe how to properly handle various situations that may arise while the weapon is being fired. The MK44 cannon is an open-breech weapon, which means that, when fire is suspended, the breech bolt is open; there is no cartridge in the barrel. During the barrel wear and performance test, over 20,000 rounds were fired without a closed-bolt stoppage. Under all normal operating conditions for this gun, an open-bolt condition is produced, and only an "unusual" fault would leave a round in a hot barrel. The following discussion regarding cook-off is only relevant for those rare situations in which both a misfire has occurred and the gun's mechanism has failed to achieve an open-bolt condition.

Two of the most serious safety concerns when firing this gun are propellant and explosive cook-off. Cook-off, also known as auto-ignition, can occur when enough heat from a hot barrel enters a chambered round, causing the premature, unintended, ignition of either the propellant or the explosive. The likelihood of initiating cook-off increases when a round remains in a hot barrel for an extended period of time, such as might occur during a misfire. In order for the crew to safely handle the misfire event, they must have an adequate amount of time to either take corrective actions or to evacuate the area in the vicinity of the weapon. The thermal analysis described in this report was undertaken to more precisely define the relationship between the number of rounds fired and the time to initiate propellant or explosive cook-off in a misfired round that remains in a hot barrel for an extended period of time. The information generated in this study will be used to develop misfire procedures for the MK44 cannon.

A wear and performance test of four candidate MK44 barrels was conducted by Boeing Ordnance at their facility in Mesa, Arizona. This test was conducted for and funded by the AAAV direct reporting program manager. The test involved firing approximately 20,000 rounds, with about 5000 rounds being fired through each of the barrels. The four barrels were identical except for the type of bore coating material (two chromium plated and two nitrided) and the rifling twist/land configuration (0 to 7.0-degree twist/16 lands, 3.75 to 7.5-degree twist/20 lands). During the test, barrel temperature data were obtained from thermocouples located at three axial positions along the length of the barrel (160-mm, 750-mm, and 2500-mm), all measured from the rear face of the tube (RFT). Since the chromium plated barrel was ultimately chosen because of its superior performance during the test, it will be the main focus of this report. Also, since the analysis approach did not include a model of the rifling geometry, no distinction could be made with respect to cook-off between the two rifling configurations tested. It is not believed that barrel heating rates near the breech section of the barrel, where cook-off is an issue, will be significantly affected by the rifling configuration.

Three different computer programs were employed during the analysis to model various aspects of the problem. These programs included the XNOVAKTC interior ballistics program for generating film coefficients and gas temperatures, the FDHEAT finite difference heat-transfer program for calculations involving only barrel heating during firing, and the ABAQUS

finite element program for modeling heat transfer between the barrel, projectile, and the environment during the misfire event. A brief description of each program follows:

- **XNOVAKTC** is a one-dimensional interior ballistics program developed by the Ballistics Research Lab (now the Army Research Lab-ARL) that has been used to predict pressure time curves and projectile velocity across a wide range of gun systems. The program also predicts heat-transfer coefficients (using a pipe flow correlation), and gas temperatures, as functions of time and axial position along the barrel. The film coefficients and gas temperatures were used as input to the FDHEAT model to drive the bore heating process at various axial positions along the barrel's length.

- **FDHEAT** is a finite difference heat-transfer program developed at Benet Laboratories to efficiently solve the gun barrel heat-transfer problem for firing scenarios involving hundreds of rounds. FDHEAT uses an axisymmetric formulation to model radial and axial conduction within the barrel as a function of time. Both convective and radiative boundary conditions can be modeled at the inner and outer surfaces of the barrel. The barrel may consist of multiple layers of different material where each layer's material properties can be functions of temperature.

- **ABAQUS** is a commercially available, general-purpose, nonlinear, finite element program developed by Hibbitt, Karlsson, and Sorensen, Inc. (HKS). It is used world-wide for a variety of applications including structural and thermal analysis.

MODELING APPROACH AND ASSUMPTIONS

The first step in the modeling process involved running the XNOVAKTC interior ballistics code for the round/barrel configuration to generate the film coefficients and gas temperatures as a function of time and axial position. The FDHEAT program was then run using these film coefficients and gas temperatures to calculate the transient temperature distribution in the barrel during a particular scenario. Output files were produced that contained the temperature distribution in the barrel just after each round was fired. The FDHEAT output temperature distribution (for a particular number of rounds fired) was then mapped onto the ABAQUS mesh of the barrel, and the ABAQUS heat-transfer solution of the barrel and projectile during the misfire event was produced. ABAQUS output results of interest included:

- Temperature profiles at barrel and instrumented round thermocouple locations for comparison with experimental data

- The transient temperature response on the inner case shoulder (for propellant cook-off prediction)

- The time required to initiate thermal runaway (i.e., explosive cook-off) at any nodal position in the explosive's element set

By performing a number of ABAQUS thermal solutions, the time required to initiate propellant and explosive cook-off as a function of rounds fired during the scenario was obtained.

Interior Ballistics Modeling and Assumptions

The XNOVAKTC interior ballistics model was run for the 30-mm PGU-15B round and the MK44 barrel, both at an initial temperature of 70°F (21.1°C). An output file containing film coefficients and gas temperatures as functions of time and axial position was generated. Since previous experience has shown that the interior ballistics results are not greatly affected by the initial barrel wall temperature, this single output file was used for all of the FDHEAT runs. The use of one interior ballistics output file does not negate the overall capability of the model to properly track the dependence of barrel heating on the initial temperature of the barrel at the time each round is fired.

FDHEAT Modeling Assumptions

Barrel Geometry and Mesh

Initially, the model was intended to be used to perform heat-transfer calculations during a single-burst firing of up to 200 rounds, immediately followed by a misfire event. After the model was developed, however, and test data became available, it became desirable to compare model predictions with barrel thermocouple data for some of the multi-burst firing scenarios that were conducted during testing, where each burst could be followed by a cool-down period of 10 minutes or more. In order to keep computer runs to a reasonable timeframe, only the first 400-mm of the barrel (starting from the RFT) was modeled. In generating the mesh, nonaxisymmetric sections of the actual barrel geometry were smoothed out in such a way as to preserve actual barrel mass. The FDHEAT mesh of the barrel was identical to the ABAQUS mesh shown in Figure 1. The receiver for the barrel (i.e., the component contacting and surrounding the breech end of the barrel) was not modeled because it would have added greater complexity to the analysis and because it was not justified during this stage of the investigation. It was also believed that heat transfer to the receiver would not be significant during a misfire event that occurred immediately after a single-burst firing scenario. By neglecting the thermal mass of the receiver, conservative predictions of peak temperature for the propellant and explosive would be possible, while eliminating the inherent uncertainty of modeling thermal contact resistance between the barrel and the receiver.

Barrel Inner Diameter (ID) and Outer Diameter (OD) Boundary Conditions

At the inside surface of the barrel, forced convection was modeled using film coefficients and gas temperatures produced by the XNOVAKTC interior ballistics program for the PGU-15B round. At the outside surface of the barrel, both natural convection and gray body radiation were modeled using, in general, a sink temperature of approximately 21.1°C (70°F). For the radiation calculation, an emissivity of 0.8 was used for the barrel's external surface. For the outer barrel surface forward of the receiver area, it was found that a convection coefficient having a value between one and two times the film coefficient obtained from the simplified natural convection film coefficient equation for horizontal cylinders in air produced results that were in good

agreement with thermocouple data for that region. On the breech region of the barrel, where the receiver is located (but not included in the model), a natural convection coefficient was used having a value between one and two times the film coefficient that was obtained from the simplified natural film coefficient equation. This small convection on the OD of the barrel in the receiver region was used to approximate, to a limited degree, the loss of heat to the receiver during actual firing. Although using a value of two times the film coefficient obtained from the simplified natural convection equation may seem like a large calibration factor, these film coefficient values are relatively small to begin with.

The simplified equation for laminar natural convection on the outer surface of a horizontal cylinder in air is given in Reference 1 as:

$$h = 1.32\left(\frac{\Delta T}{d}\right)^{\frac{1}{4}}$$

where

$$h = \text{film coefficient, } \mathrm{W/m^2 \cdot {}^{\circ}C}$$
$$\Delta T = T_{OD} - T_{ambient}, {}^{\circ}C$$
$$d = \text{diameter, m}$$

Barrel Initial Temperature

For most of the modeling runs, the temperature of the barrel prior to firing the first round was assumed to be uniform at the actual recorded barrel temperature, typically between 65°F (18.3°C) and 85°F (29.4°C). For analysis runs that were not associated with a particular experimental firing, an initial temperature of 70°F (21.1°C) was used.

Firing Rate

Unless otherwise stated, a constant firing rate of 200 rounds per minute was used for burst firing during the analysis.

Firing Schedules

Several different types of firing schedules were used during testing and in the analysis. The following list gives a description of the most important ones investigated:

- 66-Round Tactical Engagement (see Table 1) = 66 rounds in 147 seconds with each burst at 200 rpm (= 0.3 sec/shot)

- Combat Tactical Schedule = 198 rounds total: 3 x 66-round tactical engagements with 10 minutes reload time between each engagement (total time of 27:21 min:sec)

- Magazine Fire-Out Using Combat Tactical Schedule = 524 rounds total = 8 x 66-round tactical engagements (minus last four rounds) with 10 minutes reload time between each 66-round engagement (total time of 89:24 min:sec)

- Magazine Fire-Out with Continuous Burst = 524 rounds fired: 2 x (210 rounds at 200 rpm + 15 minutes reload time) + 104 rounds at 200 rpm (total time of 32:37 min:sec)

During testing, prior to the start of many of the firing schedules indicated above (primarily the 198-round combat tactical schedule), a number of warmer rounds (usually 5 rounds) and/or ambient dispersion rounds (usually around 20 rounds) were fired.

ABAQUS Thermal Analysis Description and Assumptions

General Information

The ABAQUS thermal model included a 400-mm section of the barrel (starting at the RFT), the cartridge case, and a projectile consisting of several components including the shell, rotating band, and explosive material. See the descriptions below for specific modeling details for the High Explosive Incendiary with Tracer (HEI-T) and Raufoss Multi-Purpose, Low Drag with Tracer (MPLD-T) rounds. Since propellant is a very good insulator, it was not included as a material in the model. Omitting the propellant from the model resulted in an insulated boundary condition at the inside surface of the cartridge case. Eight-node axisymmetric diffusion elements (DCAX8) were used throughout the model.

Barrel Geometry and Mesh

Figure 1 shows the ABAQUS mesh that was used to model the barrel (blue). The ABAQUS barrel mesh was identical to the mesh used in the FDHEAT analysis.

HEI-T Round Mesh

Figure 1 also shows the mesh that was used for the HEI-T round, which consisted of an aluminum cartridge case (gray) and a projectile composed of several components, including a steel projectile shell (green), a nylon/glass rotating band (yellow), and the PBXN-5 explosive (red).

MPLD-T Round Mesh

Time constraints did not permit the development of a finely detailed mesh of the interior components of the MPLD-T round. However, by modifying the HEI-T mesh, and by substituting MPLD-T material property definitions for different element regions in the mesh, it was possible to produce a solution that is believed to provide a very good thermal response for the two most important reactive components (PBXN-5, Comp-A4) in the MPLD-T round. The modified model included the steel cartridge case and a projectile having a steel shell, plastic rotating band, zirconium incendiary charge, Comp-A4 self-destruct device, and PBXN-5 explosive. Although the heat transfer through all of the reactive materials was modeled, only the

Comp-A4 and PBXN-5 explosive (because of their lower reaction temperatures) were considered candidates for explosive cook-off during an analysis run. Also, since the MPLD-T round has a slightly thicker projectile shell than the HEI-T projectile shell, the PBXN-5 explosive will cook off sooner in the HEI-T round than it will in the MPLD-T round. For this reason, the major focus of the Raufoss MPLD-T explosive cook-off study was to determine the cook-off times for the Comp-A4 explosive.

Barrel ID and OD Boundary Conditions

Since ABAQUS was used to model the heat transfer between the barrel, projectile/case, and the environment during the post-firing misfire event, there was no need to include forced convective heat transfer on the barrel's inner surface. The barrel's initial temperature distribution was predicted using the FDHEAT program for the specific firing scenario under consideration, which was then mapped onto the ABAQUS mesh to provide an initial hot barrel condition for round heating during a simulated misfire. The ID boundary conditions on the barrel involved conduction to the projectile/case through contacting surfaces where each barrel/surface pair possessed a different contact conductance value. Barrel contact with three different projectile/case surfaces—cartridge case, rotating band, and middle projectile shell—was considered during the analysis. Gap conductance and gap radiation through an air space were also modeled between the barrel and case at the case crimp and between the barrel and those exterior regions of the projectile shell that were relatively close to the barrel. Cavity radiation was modeled between the forward section of the projectile shell and the interior surface of the barrel. More specific details associated with modeling the contact conductance, gap conductance and radiation, and cavity radiation are given below.

The boundary conditions on the exterior surface of the barrel were similar to those previously discussed for the FDHEAT model with the following changes. For the outer barrel surface forward of the receiver area, it was found that a convection coefficient having a value 0.5 times the simplified natural convection film coefficient equation for horizontal cylinders in air produced results that were in good agreement with the experimental barrel thermocouple data in that region. The need for a reduction to a factor of 0.5 was most likely the result of decreased cooling due to the forward region of the barrel being enclosed in a tube containing air that was heated during prior firings. On the breech region of the barrel where the receiver is located (but not included in the model), a natural convection coefficient was used having a value four times that obtained from the simplified natural film coefficient equation. The use of a factor of four, over the factor of two used for this barrel region in the FDHEAT analysis, was seen to be a more accurate (less conservative) factor for approximating the heat sink effects of the receiver during the misfire event.

Thermal Contact Conditions

Thermal contact resistance should be modeled between the projectile/case and barrel contacting surfaces to properly account for the rate at which heat is transferred from the hot barrel to the projectile/case. Assuming perfect contact between the contacting surfaces would result in too rapid a heat transfer rate to the projectile/case and produce an overly conservative estimation of the time required to initiate propellant and explosive cook-off. In the absence of

test measurements, obtaining reasonable thermal contact resistance values can be difficult and can often be a significant source of uncertainty in modeling results. However, by using the test data obtained from the instrumented rounds, it was possible to obtain useful and realistic thermal contact resistance values at several important contact locations. It should be mentioned that thermal contact resistance might change after a round (at ambient conditions) is chambered in a hot barrel because the barrel and projectile temperatures are continuously changing, resulting in continual dimensional changes of both components. The test data, however, showed fairly consistent thermal contact resistance values at several locations of interest. Modeling the impact of barrel and projectile dimensional changes on contact resistance would be very complex and was considered to be beyond the scope of this work. The thermal contact resistance over a given contact area (A) is equal to $1/h_cA$, where h_c is called the contact coefficient. The contact coefficients used for each of the three contacting surfaces considered in the model are given below:

Contacting Surfaces	h_c (W/m^2-^oC)
Cartridge Case and Barrel ID	556
Rotating Band and Barrel ID	55,600
Projectile Shell OD and Barrel ID	473

For the contact between the projectile shell OD and the barrel, only the rifling land surface area was considered to be in contact with the shell. Perfect contact was assumed to exist between axially adjacent projectile/case components, such as the rotating band and projectile shell and the cartridge case and rotating band.

Gap Conditions

Heat transfer across the gap between the case crimp region and the barrel ID, and across the gap between the projectile shell and the barrel ID, was modeled using both gap radiation and a gap conductance. For the gap radiation calculation, the emissivity of both surfaces was assumed to be one. Gap conductance values were based on the gap thickness and the conductivity of air evaluated at the average temperature of the two surfaces.

Cavity Radiation

The heat transfer between the barrel ID and the projectile's forward OD surface was modeled using the cavity radiation capability of ABAQUS. The emissivity of both the barrel and projectile shell surface was assumed to be one.

Initial Temperatures of Barrel and Projectile Components

For cook-off prediction, the initial temperature distribution of the barrel was produced from the FDHEAT runs for a firing schedule involving the specified number of rounds under consideration. The initial temperature of the case, and each projectile component, was either set to initial thermocouple readings, if applicable, or assumed to be uniform at a value of 21.1°C (70°F).

Propellant Cook-Off Prediction

Since this weapon uses cased ammunition, heat generated by the burning propellant in the breech region will be extracted with the case after each round is fired, and will therefore not reach the barrel surface rearward of the case mouth. This means that the heat required for initiating propellant cook-off must be conducted rearward from the hotter barrel material located forward of the case mouth. Rearward conduction of heat will cause the peak temperatures on the inside surface of the case to decrease with the axial distance from the case mouth. Since the case shoulder region is the most forward position where propellant can reside, and therefore the location where the propellant will experience the hottest temperatures, it will be the most likely region where propellant cook-off will be initiated during a misfire event. As discussed above, the model used to perform the thermal analysis of the misfire event does not include the propellant material, but assumes insulated conditions on the inner case surface. This means that predicted case temperatures will be slightly higher (and thus more conservative) than actual case temperatures, owing to the fact that some of the heat that would have been received by the propellant will remain in the case.

In order to predict the time necessary to initiate propellant cook-off during the misfire event, a comparison was made between an experimentally based cook-off curve for M2 double-base propellant and the predicted time/average temperature curve (refs 2,3) for the inner surface of the case shoulder. The intersection of these two curves gives the time required to produce propellant cook-off for the misfired round. The experimental cook-off curve for M2 double-base propellant is shown (red solid curve) in Figure 8 (detailed further below). The cook-off curve in Figure 8 is another form (different units) of the simple cook-off equation given below:

$$\text{Time} = 1.029\text{x}10^{25}(\text{Temp})^{-10.95}$$

where time is the time to cook-off in minutes, and temp is the cook-off temperature in °C.

The data used to generate this curve came from a paper by M. Visnov (ref 4). Cook-off curves of this nature are generally obtained by placing a small amount of propellant on a hot plate whose surface is held at a constant temperature, and then waiting until the propellant ignites. The cook-off curve shows that as the temperature decreases, the time necessary to initiate cook-off increases. Since during a misfire, the propellant will not be resting on a surface at constant temperature, but on a surface whose temperature varies with time, some type of average predicted temperature must be used in the comparison with the constant surface temperature cook-off times of the experimental cook-off curve. The time/average temperature on the inside surface of the case shoulder was chosen as the average predicted temperature to be used in the comparison (refs 2,3). At a particular point in time after a round has been loaded, the case shoulder time/average temperature at that point in time is equal to the average of the case shoulder temperature from the time of loading to the current time as follows:

$$\text{Time Ave Temp @ t} = \frac{1}{(\text{t} - \text{t}_{\text{Load}})} \int_{t_{Load}}^{t} T\,dt$$

The time/average temperature is a good indicator of the average temperature the propellant has experienced up to the current time (since being loaded), and is for that reason believed to be the appropriate temperature for comparing with the experimental cook-off curve temperature data.

Explosive Cook-Off Prediction

When explosive material in a warhead experiences localized heating that raises its temperature above a critical level, exothermic chemical reactions begin to take place. This additional heat will tend to accelerate the chemical reaction further unless heat can be dissipated by conduction to cooler surrounding material. If the heat generation rate is high enough, and the material is unable to conduct the heat away fast enough, the localized material will experience a very rapid rate of temperature increase, known as thermal runaway, resulting in the cook-off, or detonation, of the explosive material.

Including the effect of heat generation by a reacting material into the finite element model involved adding an Arrhenius-type heat generation term to the explosive's material property definition. In ABAQUS, this was accomplished by using the *HEAT GENERATION keyword option (ref 5) and the HETVAL user subroutine (ref 5). The rate at which heat is produced in the explosive material is given by

$$\dot{q} = \rho\, Q A e^{-E/RT}$$

where

$$\dot{q} = \text{heat rate per unit volume } (\mathrm{W/m^3})$$
$$\rho = \text{density } (\mathrm{kg/m^3})$$
$$Q = \text{heat of reaction (J/kg)}$$
$$A = \text{frequency factor (1/sec)}$$
$$E = \text{activation energy (cal/mol)}$$
$$R = \text{gas constant} = 1.987 \text{ cal/mol}\cdot{}^\circ\mathrm{K}$$
$$T = \text{temperature } ({}^\circ\mathrm{K})$$

For the HEI-T round model, the potential for explosive cook-off was only considered in the PBXN-5 explosive, while in the Raufoss MPLD-T model the potential of explosive cook-off was considered for both the PBXN-5 explosive and the Comp-A4 self-destruct device. The Raufoss round did have other reacting materials that had higher reaction temperatures, and for this reason, were not considered to be explosive cook-off candidates. The material properties used in the model for the two reactive explosive materials are given below:

Material Property	PBXN-5	Comp-A4
ρ (kg/m^3)	1897	1680
Q (J/kg)	2.0934 E+6	2.0934 E+6
A (1/sec)	5.0 E+19	2.02 E+18
E (cal/mol)	52.7 E+3	47.1 E+3

The prediction of explosive cook-off in both the HEI-T round and the Raufoss MPLD-T round involved monitoring temperatures at explosive material nodal positions until thermal runaway was observed. Typically, the ABAQUS program would begin to experience numerical problems (usually floating point overflow problems) at the onset of thermal runaway because of the extremely high rates of temperature increase at the thermal runaway node. When these numerical problems were observed, it was necessary to rerun the analysis using a very small maximum permissible time increment for the remaining (thermal runaway) portion of the analysis.

TEST AND ANALYSIS RESULTS

Boeing Ordnance conducted a 20,000 round wear and performance test from 1 November 1999 to 15 December 1999 in Mesa, Arizona. Although the primary objective of the test was to assess the performance of four different barrel configurations, barrel and instrumented round thermocouple data were collected during the test. These data were used to help validate the thermal model. Thermocouple data on the exterior surface of the barrel were obtained at three axial locations: 160-mm, 750-mm, and 2500-mm from the RFT. Thermocouple data were also obtained from instrumented rounds that were loaded into hot, pre-fired barrels. The instrumented round thermocouple locations were at four internal positions (projectile middle, projectile base, case middle, and case shoulder) and are shown in Figure 2. In addition, special cook-off rounds (not instrumented) were inserted into hot barrels (previously heated by a particular firing scenario) and permitted to cook off such that the time to produce propellant cook-off could be obtained.

The test firing schedule involved over 1200 recorded events that identified different tasks associated with the test plan. These events included such things as the firing of warmer rounds, the firing of different groups of rounds for dispersion, the insertion of a thermocoupled round, the insertion of a cook-off round, the pulling of the barrel for inspection, etc. For the four barrels used during testing, there were approximately 74 events in which good thermal data were obtained. These good data were produced by any of the three barrel thermocouples, any of the four instrumented round thermocouples, or a successful cook-off round test. There were 70 events in which at least one of the three barrel thermocouples produced a good trace. Of these 70 events, 46 events showed a good thermocouple trace at the 160-mm location, with 25 coming from nitrided barrel firings, and 21 coming from chromed barrel firings. The 160-mm barrel thermocouple location was the most important barrel thermocouple location (of the three) for model calibration. There were approximately 49 events associated with instrumented round testing, 33 of which produced good thermal traces for at least one of the four thermocouple

locations. There were 23 cook-off round events, all of which produced valid data identified by either a time to cook off or a no cook-off event.

Of the 74 events that contained good thermal data, there were only three events in which the 198-round combat tactical schedule was fired through a chromed barrel (events 1015, 1018, and 1112) and which also produced good thermocouple data at both the 160-mm barrel thermocouple location and the four instrumented round thermocouple locations. These three chromed barrel events will be the primary source of thermocouple data for comparison with modeling results. Of the 23 events that produced good propellant cook-off time data, 11 events were for chromed barrels and 12 events were for nitrided barrels.

Comparison of Test Data with Analysis Results

Thermocouple test data typically contain a level of noise that can be smoothed out for a better visual comparison with the inherently smooth analysis results. Thermocouple test data plots shown in this report are the result of using 11-point smoothing, which averages the five temperatures on either side of a data point with the temperature at the data point to obtain a smoothed average temperature for the data point. This process essentially places a smooth curve through the center of the noise. Test data temperature noise levels generally oscillated by less than $\pm$ 4°F around the smoothed average temperature value.

As discussed earlier, the heat entering the barrel during a rapid-burst firing is concentrated near the bore and forward of the case mouth. Analysis results showing the temperature distribution in the barrel after a rapid-burst firing are shown in the two contour plots of Figure 3. These contour plots were generated for a burst firing of 210 rounds at a firing rate of 200 rounds per minute. The upper contour plot shows the concentration of heat immediately (i.e., 0.29 second) after round 210 was fired, while the lower contour plot shows the concentration of heat after the barrel has cooled for 31 seconds. The upper contour plot shows that the heat is concentrated forward of the case mouth, and very close to the bore surface, immediately after firing. The lower contour plot shows how the heat has radially soaked out (in 31 seconds) and has begun to conduct axially rearward, where it can impact the cook-off of the propellant.

Figures 4 through 7 show a comparison between event 1112 analysis results and test data results for three chromed barrel events (events 1015, 1018, and 1112) involving the 198-round combat tactical schedule (198Rnd-CTS). Each figure shows a comparison of the 160-mm barrel thermocouple location (160-mm-BTL) with one of the four instrumented round thermocouple locations. The three test data events all used Primex instrumented rounds that had aluminum cases. There were some factors that made it difficult to model the exact conditions that were present during a particular firing event. These factors included:

- During testing, cool barrels were placed into gun components (e.g., the receiver) that had been heated from previous firings.

- Prior to firing the primary firing scenario, such as the 198Rnd-CTS, the barrel was fired between 5 and 115 rounds for various reasons, including the firing of warmer

rounds, dispersion rounds, etc. These pre-scenario rounds introduced an axial temperature distribution into the barrel that was not precisely known for modeling purposes. There was generally at least ten minutes of cooling after the pre-scenario rounds were fired, before the primary firing scenario was initiated.

Event 1015 was the first barrel fired on the day it was tested, and had 115 rounds fired through it prior to firing the 198Rnd-CTS. Event 1018 was the second barrel fired on the day it was tested, and had 115 rounds fired through it prior to firing the 198Rnd-CTS. Event 1112 was the first barrel fired on the day it was tested, and had 20 rounds fired through it prior to firing the 198Rnd-CTS.

Figure 4 shows a comparison between the analysis and the test data for both the 160-mm-BTL (solid lines) and the projectile middle thermocouple location (PMTL) (dashed lines). The test data time scale for this and subsequent plots has been adjusted, such that time zero is at the start of the 198Rnd-CTS. The following observations can be made regarding the curves in Figure 4:

- Considering the 160-mm-BTL, the peak temperature and cool-down phase during the final 66-round firing group shows that the event 1112 analysis results are in very good agreement with the test data for events 1018 and 1112.

- The 160-mm-BTL test data for event 1015 is lower than for the other 160mm-BTL test data. A major part of this difference can be attributed to the fact that event 1015 has a time zero temperature at the 160-mm-BTL that is at least 30°F (16.7°C) lower than the other two test data curves. Adding 30°F (16.7°C) to the event 1015 160-mm-BTL test data curve would bring it much closer to the other test data and analysis curves.

- The analysis appears to under-predict the 160-mm-BTL temperature during the earlier portions of the firing scenario, but catches up to the test data at the end of the firing. One possible explanation for this is the highly sensitive position of the 160-mm-BTL. Since this location is axially positioned near the case mouth, a large amount of the heat that enters the barrel in front of the case mouth will need to go past this location as it is conducted to the cooler regions near the breech end of the barrel. The exact physical position of the thermocouple for this location will also play a dominant role in its response, since the axial temperature gradient at this location is very high.

- At the PMTL, the event 1112 analysis temperature profile shows very good agreement with the temperature profiles for the three test data events.

- A comparison with event 1112 test data shows that the analysis prediction of temperature at the PMTL is conservative for approximately 30 minutes after the projectile was loaded.

Since Figures 5 through 7 contain the same 160-mm-BTL curves (solid lines) discussed previously, only the instrumented round test data and analysis data in these figures will be discussed in the following section.

Figure 5 shows a comparison between the analysis and the test data at the projectile base thermocouple location (PBTL) (dashed lines) for the 198Rnd-CTS. The following observations can be made regarding the PBTL curves in Figure 5:

- At the PBTL, the event 1112 analysis temperature profile shows very good agreement with the temperature profiles for the three test data events.

- A comparison with event 1112 test data shows that the analysis prediction of temperature at the PBTL is conservative for approximately 30 minutes after the projectile was loaded.

- The analysis prediction at the PBTL is slightly more conservative (when compared with its corresponding test data) than the analysis prediction at the PMTL (when compared to its associated test data).

Figure 6 shows a comparison between the analysis and the test data at the case shoulder thermocouple location (CSTL) (dashed lines) for the 198Rnd-CTS. This set of curves also includes one additional curve showing the case shoulder temperature for a steel-cased round (e.g., Raufoss-MPLD round). The following observations can be made regarding the CSTL curves in this figure:

- At the CSTL, the event 1112 analysis temperature profile shows good agreement with the temperature profiles for the three test data events.

- A comparison with event 1112 test data shows that the analysis prediction of the temperature at the CSTL is conservative for approximately 40 minutes after the projectile was loaded.

- The analysis prediction at the CSTL is slightly more conservative (when compared with its corresponding test data) than the analysis prediction at the PBTL (when compared with its associated test data).

- Using a steel case elevated the peak temperature at the case shoulder by approximately 12°F (6.7°C) over the peak case shoulder temperature predicted for an aluminum case. The reason for this is most likely due to the fact that aluminum has a higher thermal diffusivity than steel and can therefore transmit heat more rapidly from the hotter case shoulder material to the cooler case material located closer to the breech. This would mean that, on average, a steel-cased Raufoss round should experience propellant cook-off sooner than an aluminum-cased HEI-T round.

Figure 7 shows a comparison between the analysis and the test data at the case middle thermocouple location (CMTL) (dashed lines) for the 198Rnd-CTS. The following observations can be made regarding the CMTL curves in this figure:

- At the CMTL, the event 1112 analysis temperature profile shows good agreement with the temperature profiles for the three test data events.

- A comparison with event 1112 test data shows that the analysis prediction of temperature at the CMTL is conservative for approximately 40 minutes after the projectile was loaded.

- The analysis prediction at the CMTL is moderately more conservative (when compared with its corresponding test data) than the analysis prediction at the CSTL (when compared with its associated test data).

The temperature profiles at the four instrumented round thermocouple locations shown in Figures 4 through 7 show that, as one moves rearward from the PMTL to the CMTL, the analysis prediction becomes increasingly more conservative than the test data. This trend is most likely the result of using a model that does not include the thermal mass of the receiver. The absence of the receiver in the model will cause predicted temperatures in the breech section of the barrel to be higher than experimental breech temperatures, which reflect the heat-sink effect of the receiver mass. Since the two thermocouple locations in the cartridge case have a greater proximity to the receiver, they are more greatly affected by the receiver's presence than the two projectile thermocouple locations.

Live Fire Propellant Cook-Off Data

A total of 23 test events produced useful propellant cook-off data during the wear and performance test. Useful cook-off data consisted of either a time to produce propellant cook-off or a no cook-off condition within the allotted time. Initially, test personnel waited 30 minutes for a cook-off to occur, but this was later increased to 45 minutes. Of the 23 propellant cook-off events, 20 events were for the 198Rnds-CTS (10 for a nitrided barrel, 10 for a chromium plated barrel) and 3 events were for the 524-round magazine fire-out with continuous burst (2 for a nitrided barrel, 1 for a chromium plated barrel). Of the 23 propellant cook-off test events, 17 events were for rounds with aluminum cases, and 6 events were for rounds with steel cases (i.e., Raufoss rounds).

Table 2 lists a summary of the propellant cook-off events for a nitrided barrel for the 198Rnd-CTS, and Table 3 lists a similar summary for the chromium plated barrel. The data in the results column for the two tables are used to identify events for which no cook-off occurred, and events for which cook-off did occur. The event for which cook-off occurred in the shortest time is in bold type. The column for pre-rounds fired indicates the number of rounds that were fired through the barrel during the hour or so time period just prior to firing the 198Rnd-CTS. For the nitrided barrel results in Table 2 there were four events that produced cook-off, with the shortest cook-off time being 10 minutes and 43 seconds (this was a steel-case round). For the chromium plated barrel results of Table 3 there were only two events that produced cook-off,

with both cook-off times being 29 minutes and 40 seconds (these were both aluminum-cased rounds).

Table 4 lists a summary of the three propellant cook-off events (two nitrided, one chromium plated) where the firing scenario used to heat the barrel was the 524-round magazine fire-out with continuous burst. As expected, all three rounds cooked off in very short times (around 2 to 3 minutes). The shortest cook-off time was 1 minute and 50 seconds and was for a nitrided barrel using a steel-cased Raufoss cook-off round.

Propellant Cook-Off Prediction for the 198Rnd-CTS Using Instrumented Round Thermocouple Data

Since the cook-off rounds used in the propellant cook-off tests did not have imbedded thermocouples to monitor the case shoulder temperature up to the cook-off event, it was not possible, for these events, to correlate actual cook-off times with those that would be predicted using thermocouple data and a propellant cook-off curve. It was, however, possible to predict propellant cook-off time using thermocouple data from instrumented round events where a cook-off round was not employed. Results of this study are presented in Table 5 for a nitrided barrel and Table 6 for a chromium plated barrel.

The layout of Tables 5 and 6 is the same as that used for Tables 2 and 3. The cook-off times presented in the results column were calculated by comparing the time/average temperature of the case shoulder thermocouple temperature profile with an experimentally based cook-off curve for M2 double-base propellant. The time at which these two curves cross is the time at which propellant cook-off is predicted to occur.

For the seven nitrided barrel cases given in Table 5, there were three events for which cook-off was predicted to occur, with the shortest predicted cook-off time being 7 minutes and 25 seconds (this was for a steel-cased round). For the seven chromed barrel cases given in Table 6, there was one event for which cook-off was predicted to occur, with its cook-off time being 13 minutes and 29 seconds (this was a steel-cased round).

This report addresses three different methods for determining the propellant cook-off time for a particular firing event:

- Method 1 uses a live fire cook-off round. The cook-off time is determined directly during the test. Results for this approach are contained in Tables 2 through 4.

- Method 2 uses an instrumented round that contains no propellant, and measures with a thermocouple, the temperature in the case shoulder region where propellant cook-off is most likely to occur. This method uses the time average of the thermocouple temperature data, along with an experimental cook-off curve for the propellant, to predict the time when propellant cook-off would occur if the propellant were present. Results from using this approach are contained in Tables 5 and 6.

- Method 3 is identical to method 2 except that the case shoulder temperature is predicted using the thermal model instead of being measured by a thermocouple. This method is the most analytically based (it only requires the experimentally based cook-off curve for the propellant) and therefore has the greatest predictive capability of the three methods. Method 3 cook-off prediction is the only method (of the three) available in the absence of instrumented round, or a cook-off round, experimental data.

Figure 8 shows temperature profiles associated with event 1112, and can be used to compare the propellant cook-off time from either method 2 or method 3. The five curves shown in Figure 8 consist of three temperature profiles that were used to make the method 2 propellant cook-off prediction given in Table 6, and two temperature profiles (generated by the thermal model) that can be used to make a method 3 prediction of propellant cook-off.

Time zero in Figure 8 is the time at which the instrumented round was loaded into the barrel. The solid red curve is the experimentally derived cook-off curve for the M2 double-base propellant and is required for making either a method 2 or method 3 cook-off prediction. The solid blue curve is the smoothed thermocouple test data that was obtained from the instrumented round at the case shoulder. The dashed blue curve showing the experimental time/average temperature at the case shoulder was obtained from the solid blue curve by using the simple time/average temperature equation previously discussed. The method 2 cook-off time can be obtained by finding the time at which the experimental time/average temperature curve (dashed blue) and the experimental cook-off curve (solid red) intersect. For this case, the two curves do not intersect at all (indicating no cook-off is predicted to occur), but come very close to intersecting (within 5°F (2.8°C)) after 30 minutes have elapsed.

The dashed magenta curve in Figure 8 for an aluminum-cased round is the analytical time/average temperature curve obtained from the analytical case shoulder temperature profile (not shown). The method 3 cook-off time for an aluminum-cased round is obtained by finding the time at which the analytical time/average temperature curve (dashed magenta) and the experimental cook-off curve (solid red) intersect. For this case, the two curves intersect at approximately 10 minutes. The method 3 cook-off time for the steel-cased round is found in a similar manner by using the green dashed time/average temperature curve, resulting in a cook-off time of approximately 9 minutes and 14 seconds.

By examining the curves in Figure 8 (which are associated with the methods 2 and 3 propellant cook-off prediction), a number of observations can be made:

- The slopes of the solid red cook-off curve and the dashed blue experimental time/average temperature curve are nearly identical after a time of 25 minutes. This would indicate that, for firing scenarios similar to the 198Rnd-CTS, although propellant cook-off would not be expected to occur in less than 25 minutes, the occurrence of propellant cook-off might occur, but be highly variable for times greater than 25 minutes since the two curves stay so close together.

- A small increase in the initial temperature of the propellant, as little as 5°F (2.8°C), would most likely result in the propellant cooking off in less than 30 minutes for this case.

- Related to the above observation, the initial temperature of the propellant must be taken into account when considering propellant cook-off potential for a given firing situation. For example, using method 2, no cook-off was predicted to occur when the propellant was at an initial temperature of 70°F (21.1°C). However, if the initial temperature of the propellant were 120°F (48.8°C) (which is possible in desert conditions) the dashed blue curve would be raised approximately 50°F (27.8°C), which would result in a method 2 propellant cook-off of approximately 8 minutes.

- The method 3 cook-off times are very conservative when compared to the method 2 cook-off times. For example, the method 3 cook-off time for event 1112 and an aluminum case is approximately 10 minutes, while there is no cook-off predicted for this case using method 2. This conservatism, as discussed earlier, is due to the thermal model predicting higher than expected temperatures in the breech section of the barrel due to the absence of the receiver in the model.

- Using method 3 and event 1112 conditions, a comparison of propellant cook-off time between a steel-cased round and aluminum-cased round shows that the steel-cased round cooks off 46 seconds earlier.

- Considering only the 198Rnd-CTS, the shortest cook-off time produced by any of the three methods was 7 minutes and 25 seconds.

<u>Propellant Cook-Off Prediction for the 524-Round Magazine Fire-Out (Continuous Burst) Using Instrumented Round Thermocouple Data</u>

Similar to what was done previously for the 198Rnd-CTS, a method 3 propellant cook-off prediction was made for the event 1205—524-round magazine fire-out (continuous burst)—and then compared to the live fire cook-off data given in Table 4. Table 4 contains the live fire cook-off data for three 524-round events (events 203, 206, and 1205). Figure 9 shows the three important thermal profiles that were used to make this prediction. Although event 1205 is a chromed barrel event, its cook-off time result is believed to be fairly close to the other two nitrided events given in Table 4. The intersection of the auto-ignition curve for the propellant with the case shoulder time/average temperature occurs at approximately 2 minutes and 14 seconds. This is the predicted cook-off time for event 1205. The live fire cook-off test data for this event showed that the round cooked off at 2 minutes and 56 seconds. The live fire cook-off tests for the two nitrided events, events 203 and 206, showed cook-off times of 3 minutes and 6 seconds, and 1 minute and 50 seconds, respectively.

<u>Explosive Cook-Off Prediction</u>

A prediction of the time required to produce explosive cook-off was made for both the HEI-T round and the Raufoss MPLD-T round. The ABAQUS finite element program was used

to model the heat transfer from the hot barrel to the projectile until explosive cook-off was predicted to occur. The prediction of explosive cook-off required the implementation of an Arrhenius-type heat generation term in the ABAQUS material definition for the reactive explosive material. Explosive cook-off was predicted for the PBXN-5 explosive in the HEI-T round and the Comp-A4 explosive in the Raufoss MPLD-T round. Cook-off of the PBXN-5 explosive in the Raufoss MPLD-T round was not pursued because the projectile shell wall thickness for the HEI-T round, being thinner than the Raufoss Round, would result in a more conservative (shorter) PBXN-5 cook-off time for the HEI-T round. The Raufoss round does have other reactive components that were not considered to be cook-off candidates because of their higher reaction temperatures when compared to the PBXN-5 or Comp-A4 explosives.

Explosive cook-off was predicted to occur when thermal runaway (previously discussed) was observed at any node within the explosive material. Figure 10 shows a plot of predicted temperature versus time at the thermal runaway node for an HEI-T projectile at round 524 of the 524-round magazine fire-out (continuous burst) firing scenario. The results in Figure 10 were generated for a chromed barrel. As can be seen in the plot, thermal runaway (i.e., explosive cook-off) occurs 2 minutes and 3 seconds after the round is loaded. Figure 11 is a contour plot that shows the distribution of temperature in the projectile and barrel at the time when the peak temperature of 806°F (430°C) occurs in Figure 10. The contour plot shows the hot spot where the explosive's heat generation is beginning to take off. The finite element node at the center of this hot spot is very close to the middle projectile thermocouple position. This hot spot node does not lie precisely on the material interface between the projectile shell and the explosive, but is slightly into the explosive material if moving from the interface.

Figure 12 shows the temperature at the projectile middle thermocouple position for several 198-round test events along with the model's prediction of the projectile middle temperature for event 1112. It should be noted that the ordinate of this graph is temperature rise (instead of simply temperature), and it is used to provide a convenient way of comparing the test data from several events (as well as the event 1112 analysis profile) that had different initial temperatures at the time the round was loaded. This graph shows how the analysis gives a conservative prediction of the projectile middle thermocouple temperature rise when compared with the five test data temperature profiles.

Figure 13 shows two contour plots that are for the same conditions as those given in Figure 11 with the exception of being at an initial temperature of 120°F (48.8°C) and for rounds 140 and 150. The lower contour plot in this figure illustrates that, for round 150, the nodal position where thermal runaway occurs is different than where it occurred for round 524 in Figure 11. The upper contour plot is for round 140 and shows that the PBXN-5 explosive is reacting and producing heat, but that not enough heat is being generated to cause thermal runaway.

The results for the cook-off of the Comp-A4 explosive are presented below.

Prediction of Propellant and Explosive Cook-Off Times, as a Function of Rounds Fired, for the 524-Round Magazine Fire-Out (Continuous Burst)

Figure 14 shows curves and data points indicating predictions of propellant and explosive cook-off times, as a function of rounds fired, for the 524-round magazine fire-out (continuous burst). The figure also shows several test data points for propellant cook-off (green circles) associated with test events 203, 206, and 1205. Predicted cook-off times are presented in the figure for two different initial temperatures, 70°F (21.1°C) and 120°F (48.8°C). This initial temperature applies to the propellant, the explosive, and the barrel, at the start of firing. A comparison of the propellant and explosive cook-off times for a given number of rounds fired shows the significant impact of initial temperature on the cook-off time. The discontinuous nature of the 70°F (21.1°C) propellant cook-off curve is the result of the 15 minutes of barrel cooling after round 210 is fired. There is also a curve in this figure showing the propellant cook-off time for a steel-cased round at 120°F (48.8°C). As this curve illustrates, and has been previously discussed, the propellant in a steel-cased round cooks off in a shorter time than the propellant in an aluminum-cased round, all other things being equal.

Explosive cook-off times are displayed in Figure 14 using hollow circles: red circles are for the PBXN-5 explosive at 120°F (48.8°C); blue circles are for the PBXN-5 explosive at 70°F (21.1°C); and the black circles are for the Comp-A4 explosive at 120°F (48.8°C). The PBXN-5 data points in this figure are for the HEI-T round. As mentioned previously, the cook-off times for the PBXN-5 explosive in the Raufoss round will be greater than those calculated for the PBXN-5 explosive in the HEI-T round because of its thicker steel shell. Therefore, the cook-off times presented in Figure 14 for the PBXN-5 will be the shortest PBXN-5 cook-off times of either the HEI-T round or the Raufoss MPLD-T round. The cook-off times for the Comp-A4 explosive (at 120°F (48.8°C)), which are only relevant for the Raufoss MPLD-T round, indicate that the Comp-A4 explosive will cook off after the PBXN-5 explosive prior to firing round 160, and at virtually the same time after firing round 160.

It should be mentioned again that the curves that are predicted in Figure 14 are believed to be conservative because they were generated using a model that does not contain the receiver mass.

Prediction of Propellant and Explosive Cook-Off Times, as a Function of Rounds Fired, for the 524-Round Magazine Fire-Out (Combat Tactical Schedule)

Similar to Figure 14, Figure 15 shows curves and data points indicating predictions of propellant and explosive cook-off times, as a function of rounds fired, for the 524-round magazine fire-out (combat tactical schedule). Propellant and explosive cook-off time predictions are presented in the figure for two different initial temperatures, 70°F (21.1°C) and 120°F (48.8°C). For both initial temperatures the graph shows that the propellant cooks off before the PBXN-5 explosive.

CONCLUSIONS

- A thermal model was developed to predict propellant and explosive cook-off times for two high-explosive rounds that will be fired through the 30-mm MK44 barrel. This barrel is employed on the Navy/Marine Corps Advanced Amphibious Assault Vehicle. The thermal model uses three separate computer programs: interior ballistics, finite difference heat transfer, and finite element heat transfer.

- The thermal model was validated using barrel and instrumented round thermocouple data previously obtained during a 20,000-round wear and performance test. The model's accuracy in predicting propellant cook-off times was validated using additional wear and performance test data obtained by measuring the time required to initiate propellant cook-off for a round loaded into a hot barrel.

- Propellant and explosive cook-off times were calculated for two 30-mm high-explosive rounds: the HEI-T and the Raufoss MPLD-T. The geometry used in the thermal model included a 400-mm length section of the barrel (with no receiver), a cartridge case, and a high-explosive projectile.

- Prediction of the propellant cook-off time was based on the intersection of the case shoulder time/average temperature profile, and an experimentally based cook-off curve for M2 double-base propellant. Both an experimentally measured, and an analytically predicted, case shoulder temperature profile were used to generate the time/average temperature profile used in the cook-off prediction.

- Explosive cook-off prediction was made using an explosive material model that included an Arrhenius heat generation term. The explosive was assumed to cook off when thermal runaway was observed at any nodal position used to define the geometry of the reactive explosive material.

- For the HEI-T round, cook-off was modeled in the PBXN-5 explosive material, while for the Raufoss MPLD-T round cook-off was modeled in the Comp-A4 explosive. The cook-off of the PBXN-5 explosive in the Raufoss round was not modeled because the thicker projectile shell thickness of the Raufoss round would produce a longer PBXN-5 cook-off time than what would occur in the PBXN-5 explosive of the HEI-T round.

- Propellant cook-off rounds tested during the wear and performance test showed that for the 198-round combat tactical schedule, and a chromium plated barrel, the minimum cook-off time measured was 29 minutes and 40 seconds. The same tests conducted using a nitrided barrel showed a minimum cook-off time of 10 minutes and 43 seconds.

- Predictions of propellant cook-off times using case shoulder thermocouple data from firing the 198-round combat tactical schedule showed a minimum predicted cook-off time of 7 minutes and 25 seconds for a nitride barrel, and 13 minutes and 29 seconds for a chromed barrel.

- Analysis results show that the propellant cook-off time for a steel-cased round will be less than that produced using an aluminum-cased round due to the lower thermal diffusivity of steel. A case material that has a low thermal diffusivity will not be able to quickly conduct heat away from the case shoulder region as the heat from the barrel conducts rearward, from the case mouth position, past the case shoulder.

- The initial temperature of the projectile and barrel play a significant role in the amount of time required to initiate either propellant or explosive cook-off in a misfired round.

- For the 198-round combat tactical schedule, and an initial round temperature of 70°F (21.1°C), the nature of the case shoulder temperature profile is such that, although propellant cook-off for a misfired round is unlikely to occur prior to 10 minutes after round loading, propellant cook-off may occur at a time that is greater than 40 minutes beyond the time the round was loaded. The possibility of propellant cook-off at such long times after the round is loaded needs to be properly accounted for in the misfire procedures that are to be written for the weapon.

- For an initial temperature of 70°F (21.1°C), the model prediction shows that propellant and explosive cook-off will not occur before firing 160 rounds for either the 524-round magazine fire-out (continuous burst) or the 524-round magazine fire-out (combat tactical schedule).

- Predictions of explosive cook-off for the Raufoss MPLD-T round show that, for the 524-round magazine fire-out (combat tactical schedule), and an initial temperature of 120°F (48.8°C), the Comp-A4 explosive will cook off prior to the PBXN-5 explosive.

- For several studies conducted to investigate the effect of thermal contact between the case and the barrel, it was found that the case shoulder temperature profile did not significantly change as the contact area in the case shoulder region was reduced. This would indicate that the low thermal mass of the case results in very fast thermal response times in the case shoulder region.

- Two graphs were generated that show predicted propellant and explosive cook-off times for the 524-round magazine fire-out (continuous burst) and the 524-round magazine fire-out (combat tactical schedule). Propellant and explosive cook-off times are given as a function of rounds fired for two different initial temperatures associated with the round, the barrel, and the environment. The two initial temperatures considered were 70°F and 120°F. Although these two graphs may indicate that the propellant cooks off prior to the explosive (or vise versa), the different level of conservatism associated with the model's results in going from the explosive location to the propellant location, make it difficult to predict which type of cook-off (i.e., propellant or explosive) will in actuality consistently happen first.

RECOMMENDATIONS

- The model can be improved by including the thermal mass of the receiver. This will enable less conservative, but more accurate, predictions to be made of propellant and explosive cook-off times.

- Some experimental results (not discussed in this report) for the 524 magazine fire-out (continuous burst) scenario showed temperatures at the 160-mm barrel thermocouple location that were higher than would be predicted by the thermal model. It is possible that barrel heating, and its associated barrel expansion, during this firing scenario could be high enough to cause blow-by of the hot gases past the rotating band. Further testing and modeling is recommended to better understand this phenomenon. It should be mentioned that, for this 524-round firing scenario, although the model predicts a lower barrel temperature at the 160-mm position, than is measured by a thermocouple, the model prediction of the propellant cook-off time for a chromed barrel is shorter (and therefore still conservative) than the measured cook-off time.

- Project managers should seriously consider a requirement that rounds/projectiles being developed for their gun system be designed with due consideration to increasing propellant and explosive cook-off times. It seems reasonable to expect that a significant increase in cook-off time could be achieved by employing an insulating material barrier between the reactive material and the highly conductive metallic projectile shell or cartridge case. A failure to consider thermal management issues during the design phase of the round may lead to safety-induced performance limitations for the weapon.

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Table 1. 66-Round Tactical Engagement

Burst Group Number	Start Time (min:sec)	Start Time (sec)	Burst Rounds Fired	Total Rounds Fired	Time to Fire Burst (sec)	Cooling Time After Burst (sec)
1	0:00	0	5	5	1.5	5.5
2	0:07	7	5	10	1.5	7.5
3	0:16	16	5	15	1.5	5.5
4	0:23	23	5	20	1.5	8.5
5	0:33	33	5	25	1.5	5.5
6	0:40	40	5	30	1.5	8.5
7	0:50	50	3	33	0.9	5.1
8	0:56	56	3	36	0.9	3.1
9	1:00	60	1	37	0.3	2.7
10	1:03	63	1	38	0.3	2.7
11	1:06	66	1	39	0.3	2.7
12	1:09	69	1	40	0.3	2.7
13	1:12	72	1	41	0.3	2.7
14	1:15	75	1	42	0.3	10.7
15	1:26	86	3	45	0.9	5.1
16	1:32	92	3	48	0.9	3.1
17	1:36	96	1	49	0.3	2.7
18	1:39	99	1	50	0.3	2.7
19	1:42	102	1	51	0.3	2.7
20	1:45	105	1	52	0.3	2.7
21	1:48	108	1	53	0.3	2.7
22	1:51	111	1	54	0.3	10.7
23	2:02	122	3	57	0.9	5.1
24	2:08	128	3	60	0.9	3.1
25	2:12	132	1	61	0.3	2.7
26	2:15	135	1	62	0.3	2.7
27	2:18	138	1	63	0.3	2.7
28	2:21	141	1	64	0.3	2.7
29	2:24	144	1	65	0.3	2.7
30	2:27	147	1	66	0.3	

Table 2
Live Fire Cook-Off Data - Nitrided Barrel

198 Round Combat Tactical Schedule					Pre-Rnds
Case	Event	Barrel Type	Cook-Off Round Used	Result	Fired
01	028	Nitrided	HJA90K019-013	17m	20
02	032	Nitrided	HJA90K019-013	No-Cook	20
03	042	Nitrided	OL-95CO81H015	No-Cook	20
04	046	Nitrided	OL-95CO81H015	No-Cook	20
05	084	Nitrided	Alliant PGU-15B	16m 10s	80
06	088	Nitrided	Alliant PGU-15B	No-Cook	0
07	098	Nitrided	Raufoss 05-RA-98	**10m 43sec**	20
08	102	Nitrided	Raufoss 05-RA-98	15m 45sec	20
09	140	Nitrided	HJA90K019-013	No-Cook	20
10	144	Nitrided	HJA90K019-013	No-Cook	0

Table 3
Live Fire Cook-Off Data – Chromed Barrel

198 Round Combat Tactical Schedule					Pre-Rnds
Case	Event	Barrel Type	Cook-Off Round Used	Result	Fired
11	1028	Chrome	Alliant PGU-15B	**29m 40s**	20
12	1032	Chrome	Alliant PGU-15B	No-Cook	20
13	1042	Chrome	PRIMEX PGU-15B	**29m 40s**	20
14	1046	Chrome	PRIMEX PGU-15B	No-Cook	20
15	1084	Chrome	Alliant ATJ97B016-001	No-Cook	20
16	1088	Chrome	Alliant ATJ97B016-001	No-Cook	20
17	1098	Chrome	Raufoss 05-RA-98	No-Cook	20
18	1102	Chrome	Raufoss 05-RA-98	No-Cook	20
19	1140	Chrome	HJA90K019-013	No-Cook	20
20	1144	Chrome	HJA90K019-013	No-Cook	20

Table 4
Live Fire Cook-Off Data – Nitrided and Chromed Barrels

524 Rnd Magazine Fire-Out With Continuous Burst					Pre-Rnds
Case	Event	Barrel Type	Cook-Off Round Used	Result	Fired
21	203	Nitrided	HJA90K019-013	3m 6s	0
22	206	Nitrided	Raufoss 05-RA-98	**1m 50s**	0
23	1205	Chrome	Raufoss 05-RA-98	2m 56s	0

Table 5
Propellant Cook-Off Prediction Using Case Shoulder Thermocouple Data and M2 Double-Base Propellant Cook-Off Curve – Nitrided Barrel

198 Round Combat Tactical Schedule					Pre-Rnds
Case	Event	Barrel Type	Round Type	Result	Fired
01	015	Nitrided	Primex	No-Cook	55
02	056	Nitrided	Raufoss	12m 17s	20
03	061	Nitrided	Raufoss	**7m 25s**	20
04	112	Nitrided	Primex	No-Cook	20
05	116	Nitrided	Primex	8m 54s	20
06	126	Nitrided	Primex	No-Cook	20
07	130	Nitrided	Primex	No-Cook	20

Table 6
Propellant Cook-Off Prediction Using Case Shoulder Thermocouple Data and M2 Double-Base Propellant Cook-Off Curve – Chromed Barrel

198 Round Combat Tactical Schedule					Pre-Rnds
Case	Event	Barrel Type	Round Type	Result	Fired
08	1015	Chrome	Primex	No-Cook	115
09	1018	Chrome	Primex	No-Cook	115
10	1057	Chrome	Raufoss	No-Cook	20
11	1060	Chrome	Raufoss	**13m 29s**	20
12	1112	Chrome	Primex	No-Cook	20
13	1126	Chrome	Primex	No-Cook	20
14	1130	Chrome	Primex	No-Cook	20

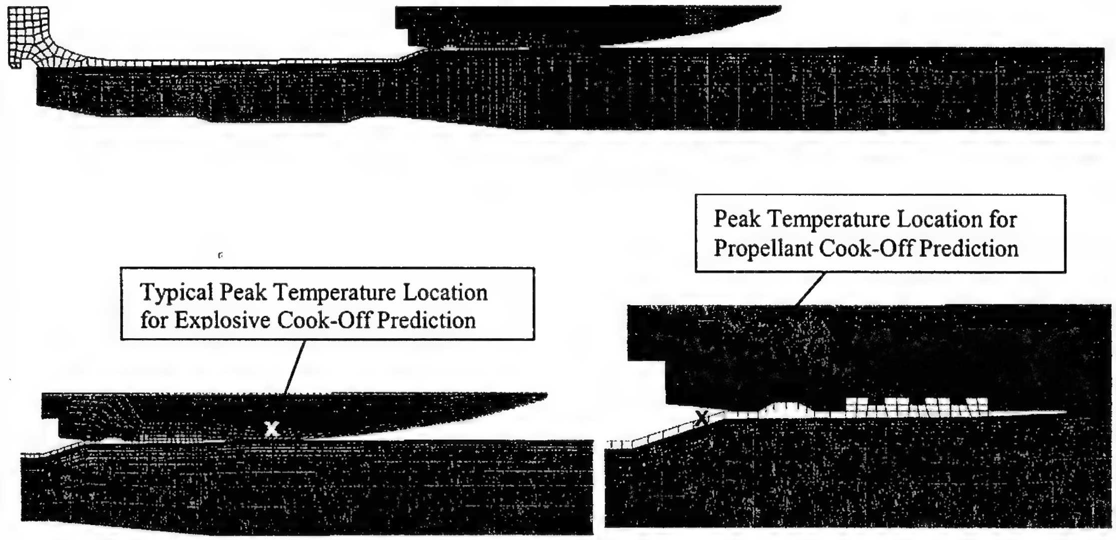

Figure 1. ABAQUS mesh used for thermal analysis of 30-mm HEI-T round chambered in a hot MK44 barrel.

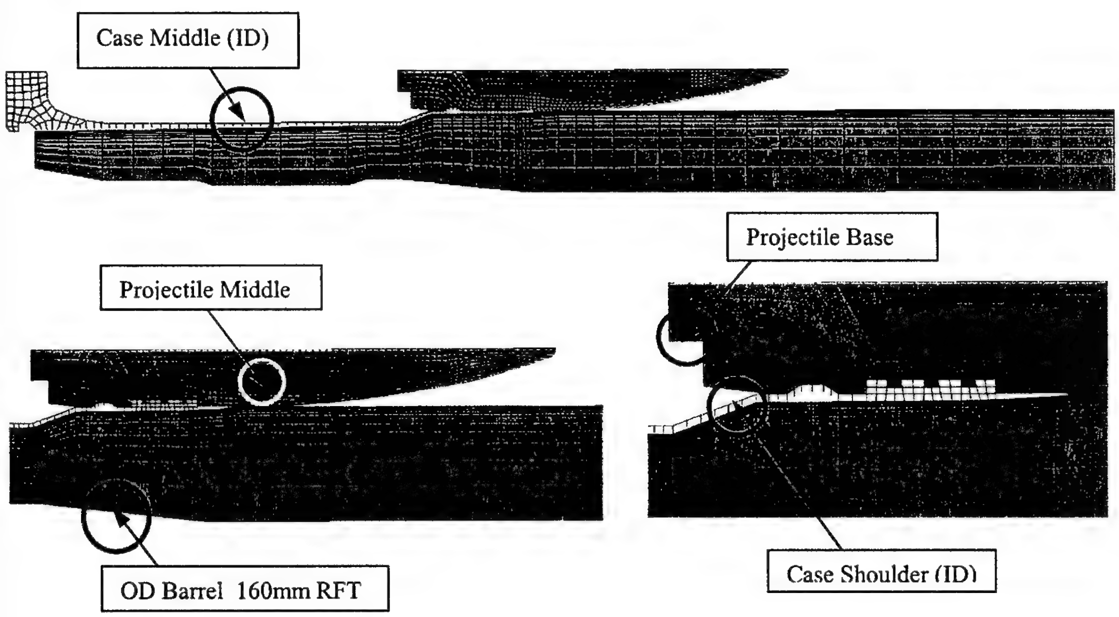

Figure 2. Instrumented round thermocouple locations.

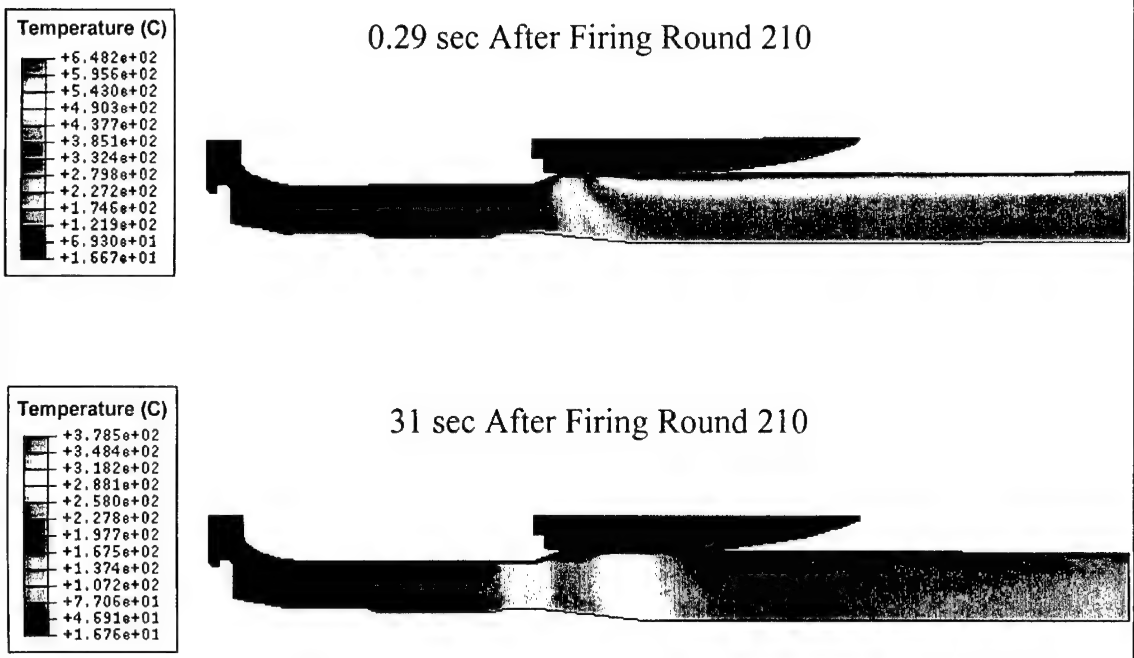

Figure 3. Concentration of heat predicted by thermal model.

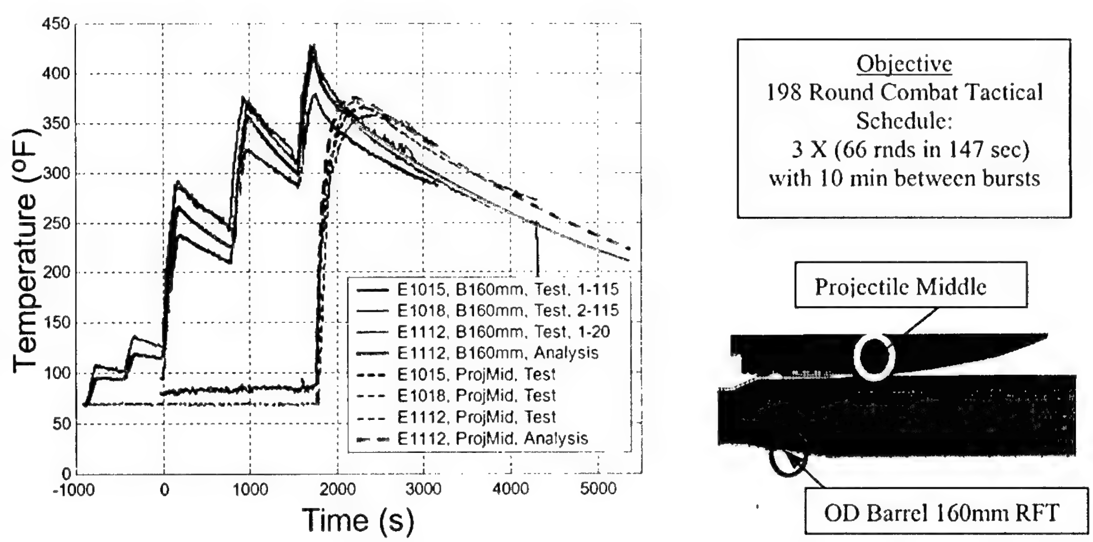

Figure 4. Comparison of analysis and test data results for the 160-mm barrel thermocouple position and the projectile middle thermocouple position, for events 1015, 1018, and 1112.

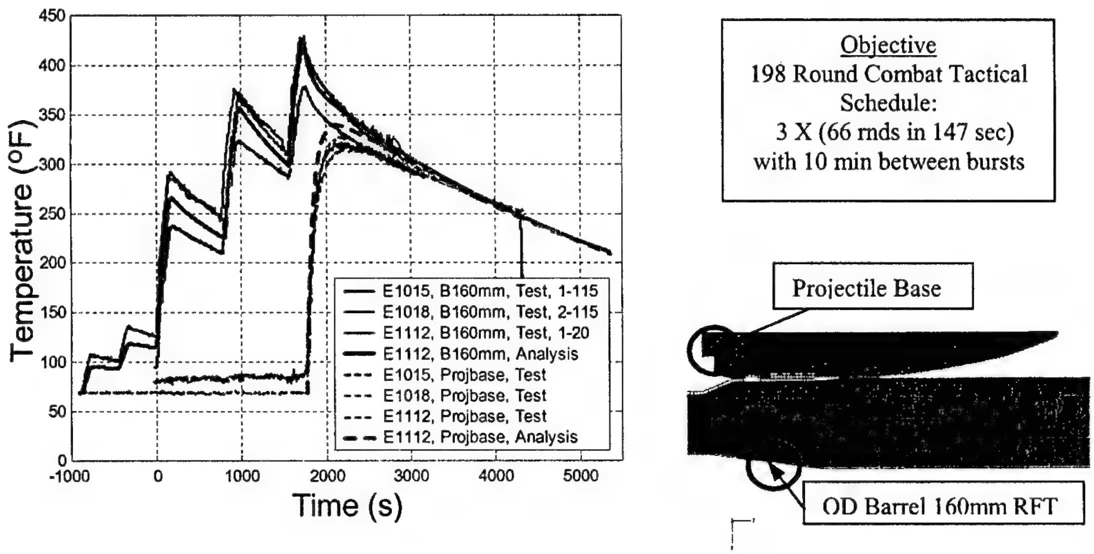

Figure 5. Comparison of analysis and test data results for the 160-mm barrel thermocouple position and the projectile base thermocouple position, for events 1015, 1018, and 1112.

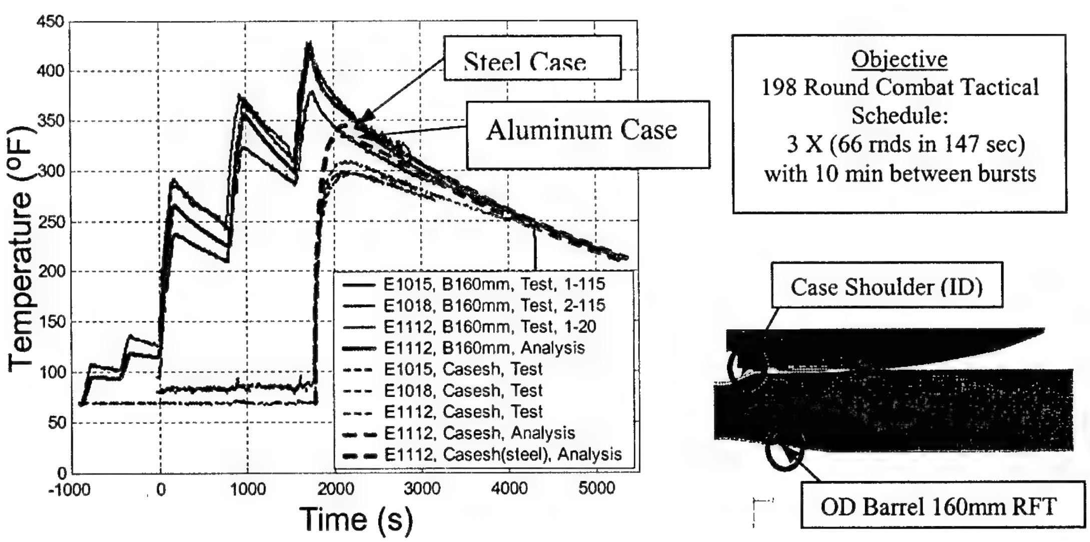

Figure 6. Comparison of analysis and test data results for the 160-mm barrel thermocouple position and the case shoulder thermocouple position, for events 1015, 1018, and 1112.

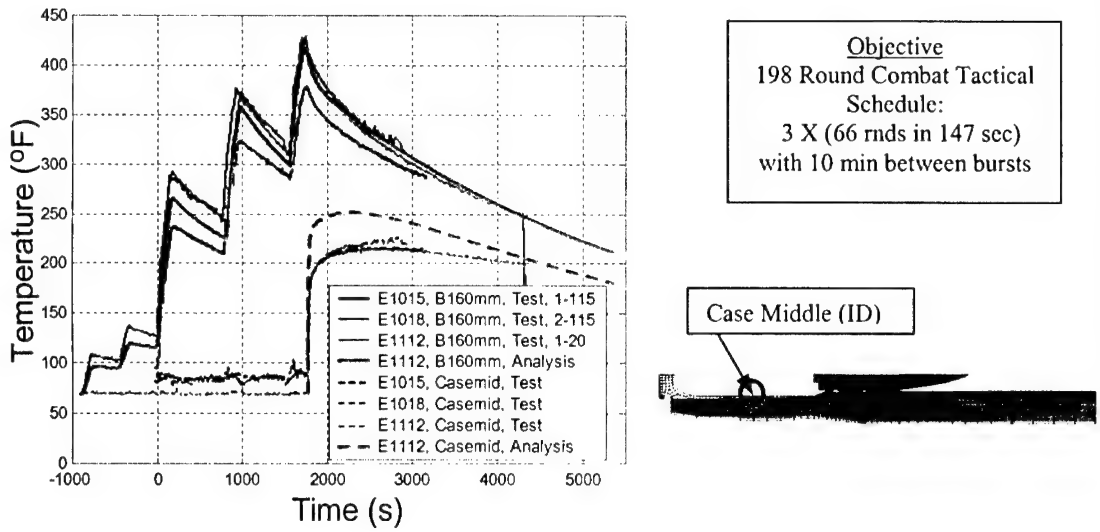

Figure 7. Comparison of analysis and test data results for the 160-mm barrel thermocouple position and the case middle thermocouple position, for events 1015, 1018, and 1112.

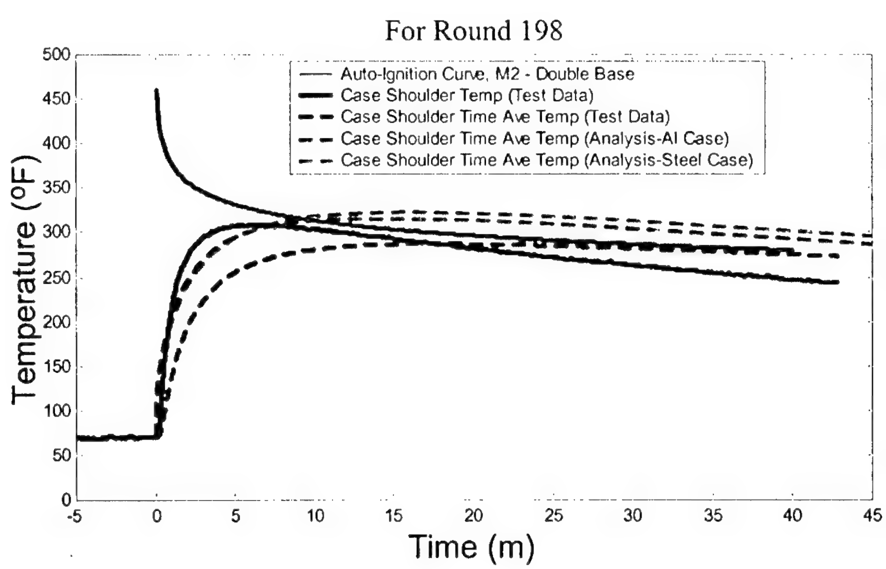

Figure 8. Temperature profiles used in method 2 and method 3 propellant cook-off prediction for event 1112.

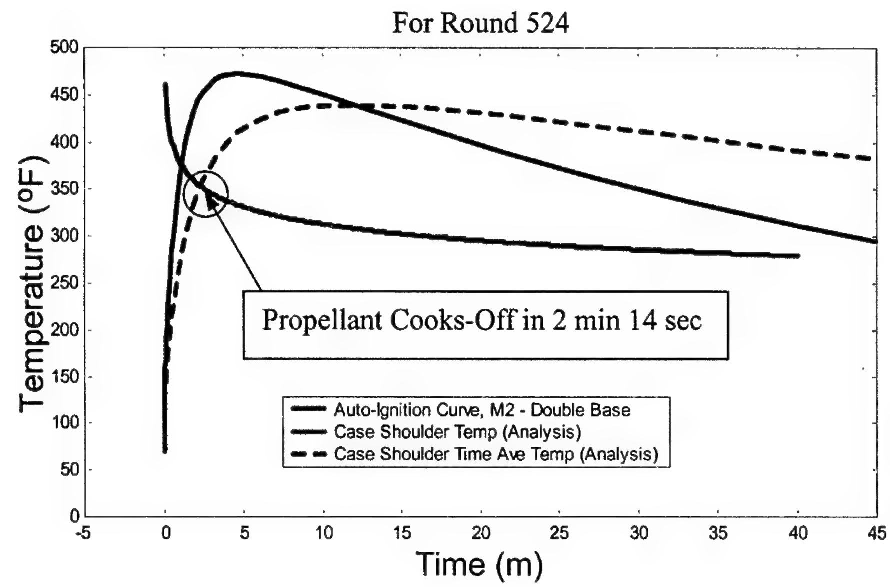

Figure 9. Temperature profiles used in method 3 propellant cook-off prediction for event 1205.

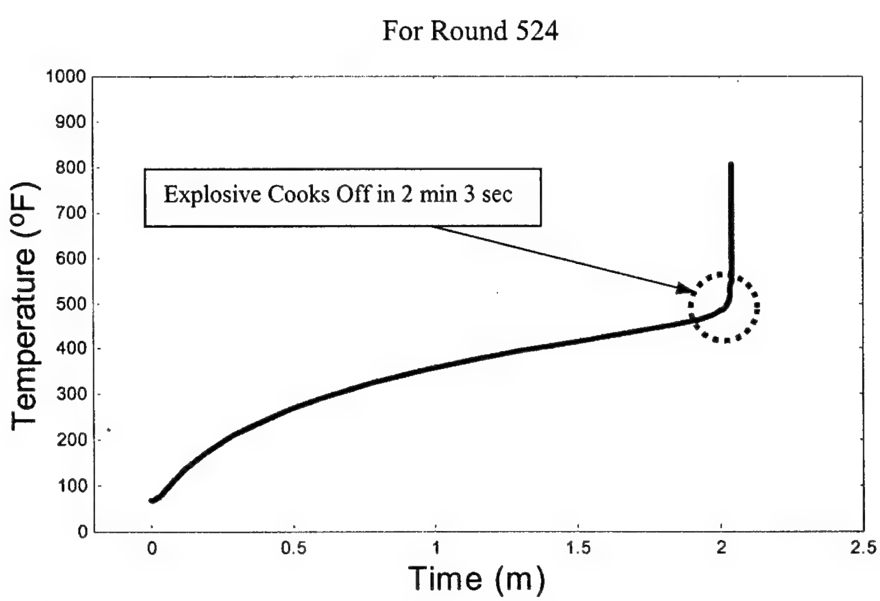

Figure 10. Predicted temperature for the PBXN-5 explosive (HEI-T Round) at the thermal runaway node.

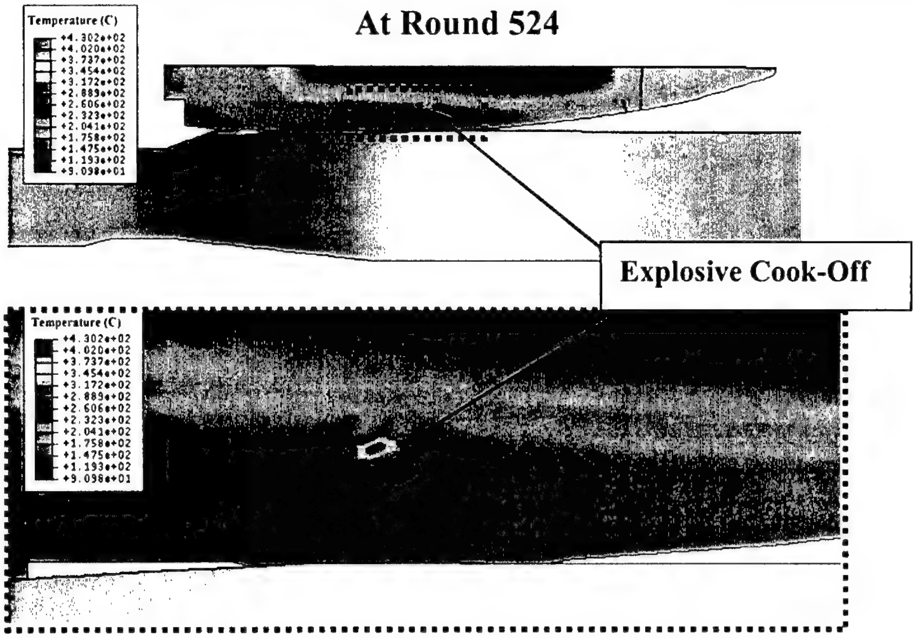

Figure 11. Temperature contour plot for HEI-T projectile and barrel at time of thermal runaway in PBXN-5 explosive.

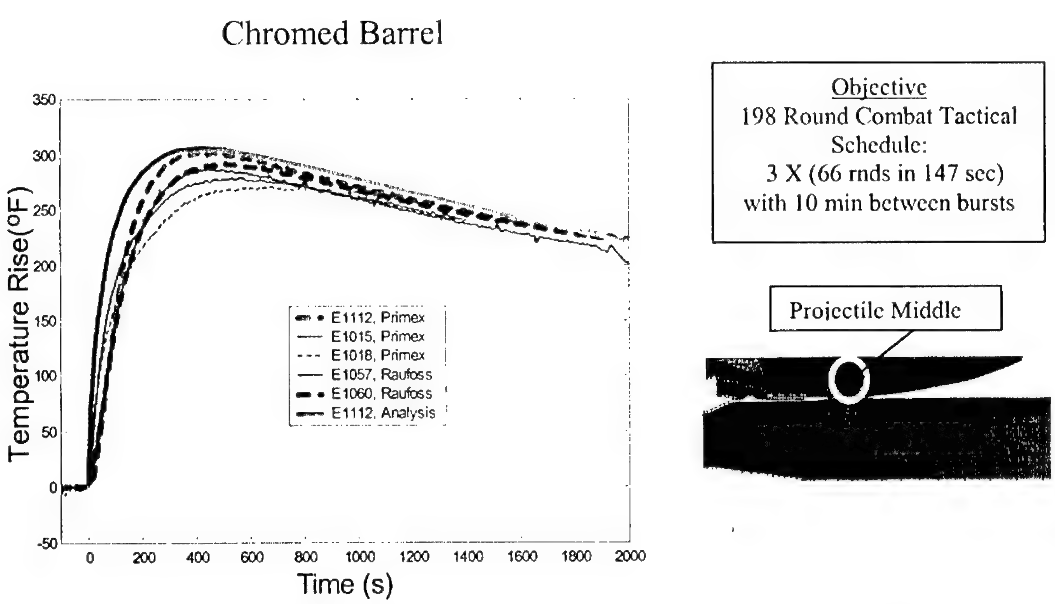

Figure 12. Comparison of analysis results with projectile middle thermocouple data for the Raufoss and Primex instrumented rounds.

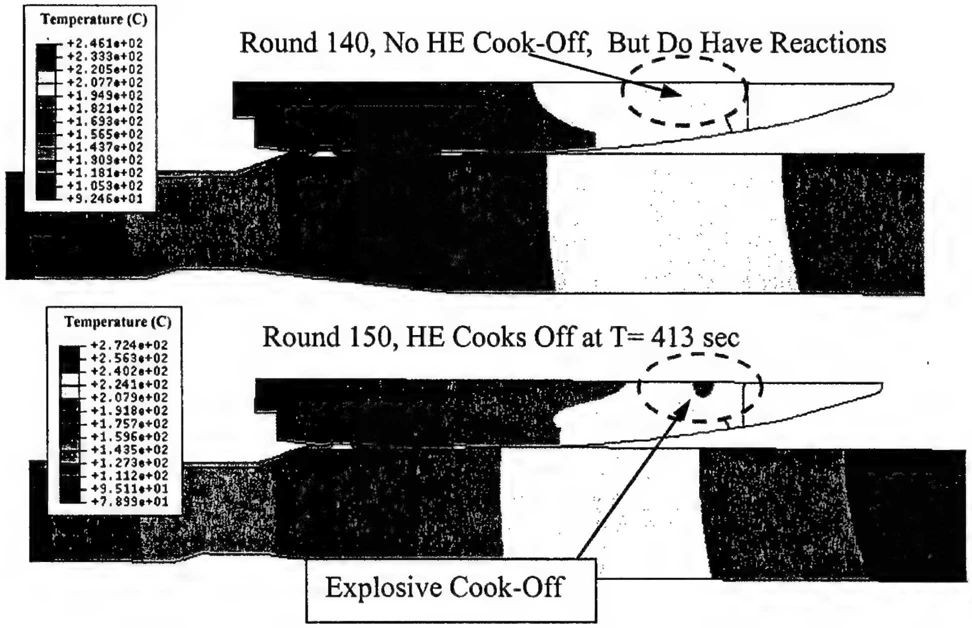

Figure 13. Temperature contour plots for HEI-T projectile and barrel at round 140 and round 150.

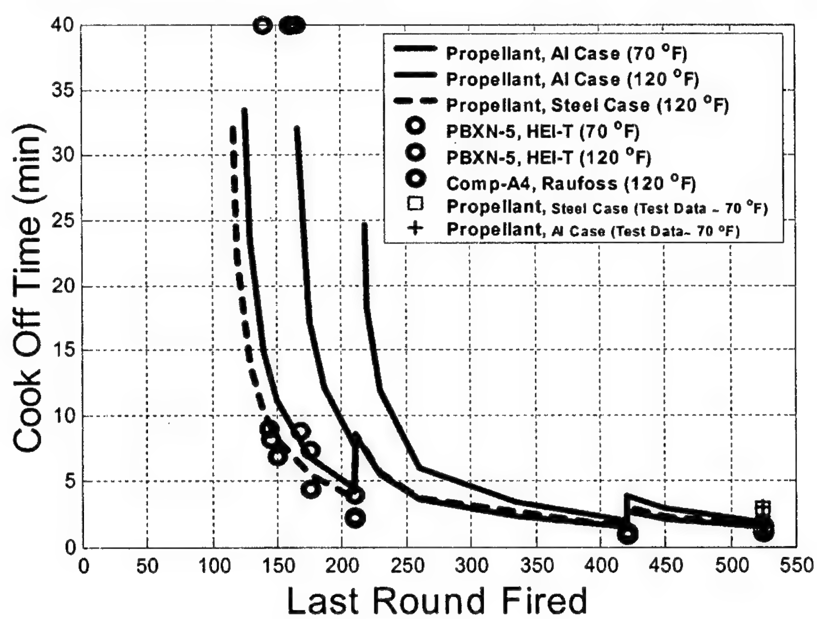

Figure 14. Prediction of propellant and explosive cook-off times for the 524-round magazine fire-out (continuous burst).

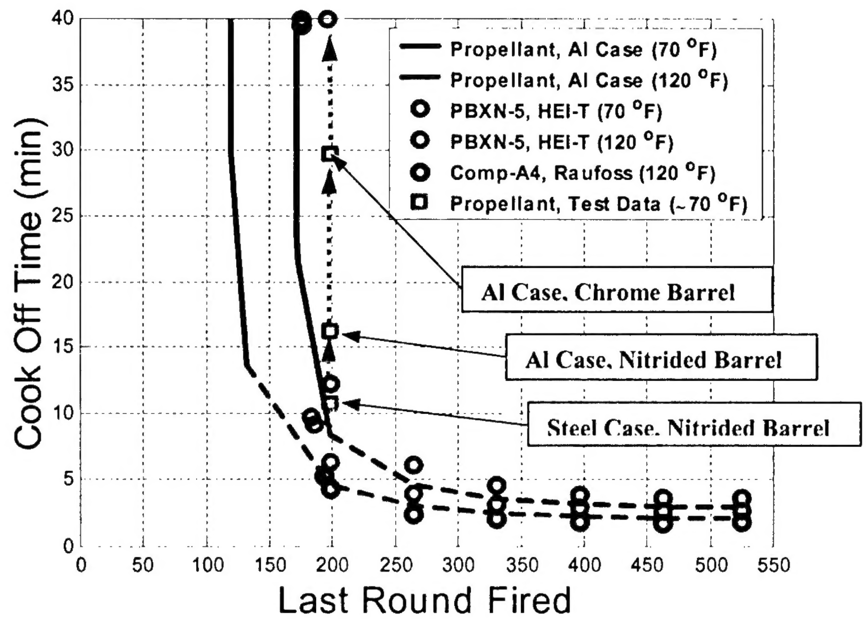

Figure 15. Prediction of propellant and explosive cook-off times for the 524 round magazine fire-out (combat tactical schedule).

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